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The quasi-harmonic ultrasonic polar scan for material characterization: Experiment and numerical modeling

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ABSTRACT

Conventionally, the ultrasonic polar scan (UPS) records the amplitude or time-of-flight in transmission using short ultrasonic pulses for a wide range of incidence angles, resulting in a fingerprint of the critical bulk wave angles of the material at the insonified spot. Here, we investigate the use of quasi-harmonic ultrasound (bursts) in a polar scan experiment, both experimentally and numerically. It is shown that the nature of the fingerprint drastically changes, and reveals the positions of the leaky Lamb angles. To compare with experiments, both plane wave and bounded beam simulations have been performed based on the recursive stiffness matrix method. Whereas the plane wave computations yield a pure Lamb wave angle fingerprint, this is no longer valid for the more realistic case of a bounded beam. The experimental recordings are fully supported by the bounded beam simulations.

To complement the traditional amplitude measurement, experimental and numerical investigations have been performed to record, predict and analyze the phase of the transmitted ultrasonic beam. This results in the conceptual introduction of the 'phase polar scan', exposing even more intriguing and detailed patterns. In fact, the combination of the amplitude and the phase polar scan provides the complete knowledge about the complex transmission coefficient for every possible angle of incidence. This comprehensive information will be very valuable for inverse modeling of the local elasticity tensor based on a single UPS experiment.

Finally, the UPS method has been applied for the detection of an artificial delamination. Compared to the pulsed UPS, the quasi-harmonic UPS (both the amplitude and phase recording) shows a superior sensitivity to the presence of a delamination.

1. Introduction

Already in the early 1980s, the ultrasonic polar scan (UPS) was introduced and presented as a sophisticated means for non-destructive testing of fiber-reinforced materials [1]. Contrary to the classical C-scan, the ultrasonic polar scan records the transmitted amplitude of an ultrasonic pulse for a wide range of liquid–solid interface incidence angles $\psi(\varphi,\theta)$. In recent years, the technique has been demonstrated to be a powerful means for composite materials, in particular for (i) the determination of the fiber direction, (ii) the detection of damage, (iii) the monitoring of the fiber volume fraction and (iv) the quantitative characterization of the local mechanical elasticity tensor of an orthotropic material [2–9].

Till now, the UPS experiments have always been performed using short ultrasound pulses, resulting in polar images with characteristic contours that correspond to the position of critical bulk wave angles. These recordings, as illustrated in Fig. 1 for both an isotropic aluminum and an orthotropic $[0_8]$ carbon/epoxy laminate, form a unique fingerprint of the material [6,10,11]. The color scale corresponds to the transmitted amplitude value, normalized to the amplitude of the incident ultrasonic pulse. Note that the central point of a polar plot corresponds to the classical C-scan recording, i.e. the sound impinges at normal incidence $\psi(\varphi,\theta) = (0°,0°)$ onto the plate of interest.

With reference to Fig. 1, the observed characteristic dips (black lines and zones) in amplitude represent those positions at which a bulk wave is generated traveling parallel to the liquid–solid

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interface (also called lateral wave). The characteristic contours in Fig. 1 have been explicitly labeled according to the nature of the corresponding wave type: L, SH respectively SV for the longitudinally, shear horizontally respectively shear vertically polarized bulk wave. As expected for a material with isotropic symmetry, the characteristic patterns are perfect circles with the SH and SV contours on top of each other (degenerated bulk waves). In the case of transversal isotropy, it can be readily seen that the contours have a non-circular shape, while the SH and SV contour are only degenerated along the fiber direction ($\varphi = 0 + k\ 180$). Since only three types of polarizations exist for traveling bulk waves, corresponding to the three solutions prescribed by Christoffel's equation [12,13], only three contours may exist in a pulsed polar scan experiment.

Recent work on plane wave numerical computations, based on the direct matrix technique, revealed that the use of mono-frequency ultrasound (also called continuous waves) in polar scan simulations generates a quite different fingerprint of the material under consideration. Contrary to being linked to the critical bulk wave angles, the characteristic contours resulting from a numerical simulation of harmonic excitation were found to be related to the stimulation of Lamb waves [10,14]. So far, this premise has not been checked or explored experimentally.

In this paper, we introduce and comment on several noteworthy extensions of the conventional UPS technique. To begin with, we report about the first time ever experiments of ultrasonic polar scans using quasi-harmonic sound pulses (i.e. bursts of periodic cycles). In addition, because of the initially discovered poor agreement between the experimental recordings and existing plane wave simulations [14], a more advanced numerical model is implemented which accounts for the angular spectrum of the experimentally employed sound beam. In the following, we refer to this numerical model as 'bounded beam simulation'. Further, since a quasi-harmonic wave can be fully described by the combination of its amplitude and phase, we extended the conventional amplitude recording toward the phase recording of the transmitted wave.

After a brief description of the experimental recording and numerical simulation approach in Section 2, a comparison (at a fixed orientation angle φ) is made between experiment, plane wave simulation and bounded beam simulation at several driving frequencies, for the simple case of an isotropic (aluminum) sample. Next, experimentally recorded and numerically computed quasi-harmonic ultrasonic polar scans for isotropic, orthotropic, cross-ply orthotropic as well as hybrid cross-ply orthotropic samples are discussed. In Section 4, we introduce the phase polar scan and illustrate the level of detail in the phase results as a complement for the amplitude scans. Finally, we demonstrate in Section 5 the benefit of a quasi-harmonic UPS over a pulsed UPS for what concerns the detection of a delamination in thin carbon/epoxy laminates.

2. Quasi-harmonic UPS: Experimental and numerical approach

2.1. Experimental setup and typical results of a quasi-harmonic UPS

The UPS experiments reported in this study have all been obtained in transmission with an in-house developed robot having 5 axes of freedom [15]. The geometry of the material under consideration is plate-like (at least locally, gentle curvatures may be treated as well). To enhance the coupling efficiency of the ultrasonic wave, the solid plate of interest is immersed in water. After a calibration and alignment phase, a rigid arm with two transducers of the same type is rotated and translated automatically to explore the transmission of ultrasonic waves at various angles of incidence. Typically, each polar scan experiment exists of more than 1 million different incidence angles $\psi(\varphi,\theta)$. To limit the amount of experimental time, the recorded signal in transmission is processed on-the-fly with a dedicated data-acquisition module. Depending on the modality, pulses or quasi-harmonic waves can be emitted while the processing can be adjusted to either amplitude, time-of-flight or phase analysis. At present, the experimental time takes about 15 min, post-processing included. However, in the future we expect that this duration can be significantly reduced through the use of Phased Array (PA) or Phased Matrix (PM) technology [16]. In addition, several difficulties in the current experimental recording, related to the mechanical scanning [15], can be circumvented with such kind of PA/PM technology.

The recorded quasi-harmonic polar scan experiment for isotropic aluminum and orthotropic $[0_8]$ carbon/epoxy are shown in Fig. 2. Each quasi-harmonic pulse consists of at least 10 sinusoidal periods, in which the outer two cycles are ignored during the post-processing in order to avoid transient effects. Although the general view of the patterns still reflects the (an)isotropy of the insonified material, a clear change of the fingerprint can be observed with respect to the fingerprint obtained for the pulsed ultrasonic polar scan recordings (see Fig. 1). It will be shown in the remainder of the text that the contours in the quasi-harmonic regime are linked to the stimulation of leaky Lamb waves, rather than to the stimulation of lateral waves.

2.2. Numerical simulation

During the late 80s and early 90s, several quasi-analytical techniques have been introduced for the numerical simulation of ultrasonic wave interaction with multidirectional composites: transfer

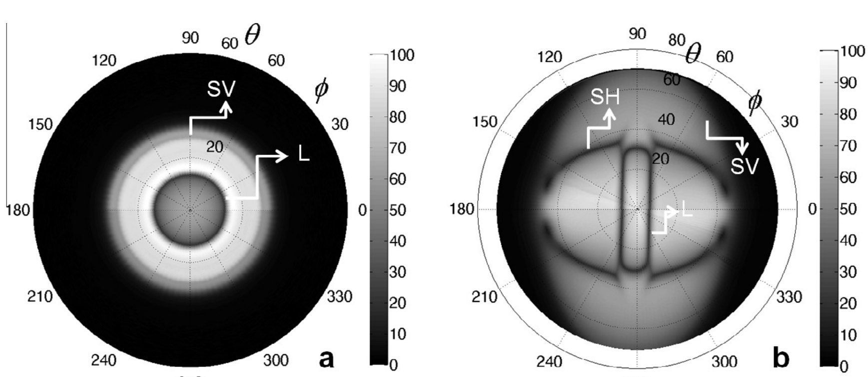

Fig. 1. Recorded pulsed UPS for (a) aluminum and (b) $[0_8]$ carbon/epoxy laminate. The characteristic contours correspond to the different critical bulk wave angles for the longitudinal (L), the shear horizontal (SH) and the shear vertical (SV) polarization.